BULK COMPOSITION OF THE MOON AS CONSTRAINED BY THORIUM DATA: COMPARISON OF LUNAR PROSPECTOR VERSUS APOLLO GRS RESULTS

Paul H. Warren and Teri L. Humphrys
Institute of Geophysics, UCLA, Los Angeles, CA 90095-1567 (pwarren@ucla.edu)

The Lunar Prospector gamma-ray spectrometry (LP-GRS) data set for thorium distribution across the global lunar surface [1] provides key constraints on the composition of the Moon's crust, with major implications for the bulk composition and gross igneous evolution of the Moon. Lawrence et al. [1] chose to derive the calibration between count rate and concentration without reference to ground truth information, referring only to the processes involved in the creation and detection of lunar γ-rays. This was in essence a highly commendable approach, as the data set of [1] can be trusted to be completely unbiased by preconceived notions or other extraneous constraints. However, as noted previously [2,3,4], additional constraints are available to test the calibration. Two of the Apollo missions flew GRS detectors, which altogether mapped about 1/5 of the lunar surface. In this work, we have integrated LP-GRS data [1] for 38 regions defined by the Apollo GRS team [5], in order to compare the two calibrations.

Results are shown in Fig. 1, where the *y*-axis indicates the magnitude of the differential Δ between LP-GRS [1] and Apollo [5] calibrations for each of the regions studied. For example, for region 31 of Metzger et al. [5] (representing Orientale's rings), the result of [5] was 0.41±0.10 µg/g, the result using the LP-GRS data set of [1] is 1.27µg/g, so the differential is (1.27-0.41 =) 0.87 µg/g. This turns out to be a very typical result.

Using all of the 38 regions studied, the average Δ is 0.78±0.45. However, the scatter is greatly reduced if we restrict the comparison to low-Th regions. Considering only the 12 regions with Th concentration (in the Apollo [5] calibration) <1 µg/g, the average Δ is 0.88±0.11. This subset of low-Th regions represents all of the limb and farside regions in our study, except for the (ever-exceptional) Van de Graff. There may be several reasons for the higher scatter in Δ results for nearside regions. These regions' higher absolute Th concentrations (however calibrated) probably translate into greater (absolute) uncertainty in the LP-GRS and especially the Apollo GRS measurements, and it is the absolute errors that determine Δ. Also, the nearside regions are more heterogeneous (in terms of absolute µg/g Th differentials), and the nearside highland regions are also generally smaller, than the farside regions of this study. Our Δ results for 10 large maria on the nearside average 0.60±0.16, in decent agreement with the 0.88±0.11 µg/g for the Th-poor farside and limb highlands. The data hint at a small systematic difference (negative slope, on Fig. 1) between Δ for the Th-poor farside/limb highlands versus the Th-rich nearside maria.

As calibrated by [1], the LP-GRS data imply the average global surface Th = 2.4 µg/g. However, Warren [2,4] (cf. Jolliff et al. [3]) found that using Apollo and Luna samples of documented collection location for ground truth, a miscalibration of ~ 1.6 µg/g is inferred for the zero under the LP-GRS calibration of [1]. A similar offset of ~ 1.0 µg/g is implied by comparison with the global regolith Th spectrum as constrained using mainly lunar meteorite regolith breccias [4]. Warren [4] noted that the same zero-offset problem is manifested by comparison with Lunar Prospector data [6] in terms of Th/K ratio: Ground truth data plot consistently to the high Th/K side of the Prospector data trend. The simplest way to improve the calibration is to subtract a constant the zero-offset Z_0 from each Prospector Th result, and then make an ad hoc adjustment (dampening) for negative or otherwise too-low results. A balancing of the available constraints on the magnitude of the offset suggests Z_0 ~ 1.2 µg/g. This recalibration brings the average global surface Th to 1.37 µg/g (in agreement with [5]).

Profound implications are manifold. The Moon's remarkable global asymmetry in KREEP abundance is even more pronounced than previously supposed. The surface Th concentration ratio between the hemisphere antipodal to the Procellarum basin and the hemisphere centered on Procellarum is reduced to 0.27 in the new calibration. This extreme disparity is most simply interpreted as a consequence of origin of Procellarum at a time when the Moon still contained at least a thin residual layer of globe-wide magma ocean [7]. Allowing for diminution of Th with depth, the extrapolated bulk-crustal Th is ~ 0.73 µg/g. Further extrapolation to bulk-Moon Th yields ~ 0.07 µg/g, nearly identical to the consensus estimate for Earth's primitive mantle.

This estimate for thorium can serve as a cornerstone for estimating the overall composition of the Moon. Assuming chondritic proportionality among refractory lithophile elements implies Al_2O_3 ~ 3.9 wt% and CaO ~ 3.1 wt%.

Another key parameter for estimating Moon's bulk composition is its bulk-mantle *mg* ratio. Contrary to occasional claims, this parameter is only weakly constrained by seismic and mare-basaltic data. Highland samples are at least equally enlightening. KREEP- and mare-free lunaite regolith samples, other thoroughly polymict lunar meteorites, and a few KREEP-free Apollo highland samples

(North Ray crater regolith and clast 14076,1) manifest a remarkable anticorrelation on a plot of Al_2O_3 vs. *mg* (Fig. 2). This trend can be extrapolated in various ways, but it clearly implies that an important component of the Moon is highly magnesian. The bulk Moon is inferred to have an Earth-like oxide *mg* ratio of ~ 87-88 mol%, implying (with MgO ~ 36 wt%) FeO ~ 9.1 wt%.

References: [1] Lawrence D. et al. (2000) *JGR* **105**, 20307. [2] Warren P. H. (2000) *LPS* **31**, 1756. [3] Jolliff B. L. et al. (2000) *JGR* **105**, 4197. [4] Warren P. H. (2003) *MaPS*, submitted. [5] Metzger A. E. et al. (1977) *PLSC* **8**, 949. [6] Prettyman T. H. et al. (2002) *LPS* **33**, 2012. [7] Warren P. H. (1998) in *Workshop on New Views of the Moon* (B. L. Jolliff and G. Ryder, eds.), 75.